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Fluid-driven reactivation of unfavorably oriented faults for the 2017 Pohang earthquake sequence

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The 2017 Mw 5.4 Pohang earthquake has been suggested to be induced by fluid injection from the nearby Pohang enhanced geothermal system (EGS). The temporal and spatial distribution of hypocenters (depth range: 2.5−7 km) including 6 foreshocks and 3,240 aftershocks as well as the mainshock recorded by our local seismic array for 340 days suggests a complex geometry and evolution of rupture segments. The initial rupture, based on 3-hour seismic data after the mainshock, consists of a main segment (N30E (strike)/51NW (dip), 3.5 km long; MS) and a subsidiary one (N10E/47NW, 1.5 km long; SS1) extending from the northeastern tip of MS. The fault slip of MS and SS1 is dominated by reverse and strike slips, respectively. The second subsidiary segment (N8E/58NW, 2 km long; SS2) has propagated from the northern tip of SS1. Toward southwest, the main segment (MS) has propagated further (∼ 1.4 km more) from the first 3-hour configuration. Then, the third subsidiary segment (N67W/83SW, 1 km long; SS3) has developed at the southwestern tip of MS, almost perpendicular to MS. The fourth subsidiary segment (N13E/55NW, 2 km long; SS4), subparallel to MS, crosscuts SS3.

The aftershock sequence shows that the frequency decreases with the reciprocal of time, following Omori's law, until 83 days after the mainshock and then there was a sudden surge of aftershock frequency with an ML 4.6 event (2018.02.11), followed by another Omori's-law decay. The timing of SS3 development corresponds to the aftershock surge with the ML 4.6 event. The calculation of Coulomb stress change caused by the mainshock shows that there is a significant increase in stress (∼ 1 bar) around SS3. All these suggest that SS3 is an independent rupture triggered by the mainshock.

Focal mechanism solutions of the Pohang earthquake sequence show strike-, reverse-, or oblique-slip faultings without any normal-slip component. Stress inversion of these focal mechanism solutions generates nearly horizontal $\sigma 1$ (109(trend)/8(plunge)) and $\sigma 2$ (18/6) with subvertical $\sigma 3$ (252/81), indicating a compressional regime. The stress ratio, R = ($\sigma 1$ - $\sigma 2$)/($\sigma 1$ - $\sigma 3$) = 0.89, is rather high, suggesting a permutation of $\sigma 2$ and $\sigma 3$ is highly likely. Using orientations of these principal stresses and rupture segments, and assuming a frictional coefficient of 0.85 (based on Byerlee's law for $\sigma n<200$ MPa since the lithostatic pressure at the hypocentral depth of the mainshock is ca. 113 MPa), Sibson's (1985, https://doi.org/10.1016/0191-8141(85)90150-6) reactivation criterion shows that the angle between $\sigma 1$ and rupture segments on $\sigma 1 \sigma 3$ plane (55-67°) is all higher than the frictional lockup angle (∼50°). This requires an abnormaly low static friction or high fluid pressure for slip reactivation of the rupture planes of the Pohang earthquake. The development of ubiquitous sand blows with fluid discharge around the epicenter during the mainshock and its hypocenter in the immediate vicinity of the injection well suggest that overpressurized fluid should have played an important role in the 2017 Pohang earthquake event.